

## THE POSSIBLE STRUCTURE AND ROLE OF NEURONAL SMART MECHANISMS IN VISION

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### Abstract

Smart mechanisms perform some seemingly complex feat without utilizing the intermediate steps, the operations, in which our favourite theories analyze that achievement. The smart solution is more direct, special purpose and it capitalizes on the specific structure of the task domain. The smart machine is made from smart special purpose components.

Application of the metaphor to the nervous system requires some insight into the neuronal construction set. It will be argued that the primary neuronal operators at the subcellular level are relatively few in number and relatively general purpose, like those for summing, comparing, gating, etc. The combination of these primary operators can lead to more sophisticated secondary operators, roughly at the cellular level, like those for coincidence detection, correlation, etc. It is the combination of these more complex operators in special-purpose spatio-temporal structures, *remappings*, which leads to task-specific brain programs, the neuronal smart mechanisms.

In this paper the visual system is viewed as a multiplicity of smart modules. The smart modules having to do with sensorily guided behaviour have direct access through the body surface (a 'window') to the world. They use information from the external world, not from an intermediate internal representation, an inner screen. To this end the sensorium and motorium have to be functionally 'transparent' to the smart modules. Some examples are discussed of modules to which the sensorium is transparent.

It is shown that the smart-mechanism approach to the study of biological (natural) information processes is very promising. It is then argued that this approach might provide a better basis for the study of perceptual cognition ('knowing by perceiving') than 'representational', 'mediated', 'inferential', or 'computational' approaches.

### 1. The Concept of Neuronal Mechanism

Higher-order variables, affordances (Gibson 1979), projective invariances (Johansson et al. 1980), time-to-contact or time-to-nearest-approach (Lee and Young 1985) are often said to be 'picked up directly', because the organism is tuned to them.

The neuronal subsystems reacting 'directly' or 'resonating to' these higher-order aspects of the visual environment were appropriately called 'smart mechanisms' by Runeson (1977). The defining characteristics are (op. cit.):

1. Smart mechanisms directly register variables of high informational value to the perceiving organism, without necessarily beginning with the registration of variables which are basic to physics or chemistry.
2. Smart mechanisms are constructed from special-purpose components rather than from 'rote' mechanisms. They capitalize on the peculiarities of the situation and task.

The concept can play an important role in attempts to bridge the gap between behavioural and neurobiological observations or theories. Also in the discussion between adherents of 'direct' and of 'mediated' (or 'inferential') theories of perception the concept of smart mechanisms can point the way to a synthesis.

### 2. Evidence for a Smart Mechanism in Vision

Many examples of smart mechanisms which might play a role in visual orientation and navigation can be found in the neurobiological literature. Let us abstract a few examples from an impressive review by Wehner (1981) on spatial vision in arthropods.

- Insects may use the dorsal light response to stabilize roll movements. Under natural conditions skylight creates an up-down intensity gradient which seems to directly control the dorsal light response. Ultraviolet receptors contribute to this response in several species. The intensity gradient is even present on moonlit nights and can also be exploited by several species of nocturnal insects. Visually guided roll-compensation is thus based directly on an informative ecological variable, the up-down intensity gradient.

- Wiersma and coworkers (e.g. Wiersma et al. 1977) have found a class of space-constant receptive fields in crustaceans that always signal the line of the horizon, independent of the actual position of the eyestalk relative to the horizon. Wilson (1978) has proposed that locust ocelli mediate the detection of the horizon and contribute to roll-compensation. Horizon-detectors

would certainly qualify as smart mechanisms or components of smart mechanisms. Again they are tuned to an informative aspect of the normal environment without much concern for basic physical variables like photon flux, spectral composition of the light and the like.

- The wide-field movement detectors in flies, bees and many other insects appear to play a role in optokinetic course control. Four types of whole-field direction-selective movement-detecting neurons have been found, which are preferentially sensitive to forward, backward, upward and downward movement respectively. These could be smart components of a visual control of roll, pitch and even yaw. The units do not habituate, as so many other neuronal circuits do, and from a functional point of view this is part of their smartness.

The use of light polarization information in orientation and navigation is another example one could elaborate on. In a wider context of non-visual smart mechanisms one could elaborate on the electro-receptive systems in several species of fish, echo-location by bats, compass-orientation mechanisms, etc. The conclusion from this must be that examples of smart mechanisms are not hard to find in the domain of perceptually-guided animal behaviour.

### 3. Smart Mechanisms as Brain Programs

Runeson (1977) and Runeson and Bingham (1983) amplify criterion 2 (the special-purpose character) of smart mechanisms by suggesting that smart mechanisms should not contain any rote mechanisms at all, not even at the sub-component level. From a neurobiological perspective such a suggestion is problematic and I will not adopt it. Basic neuronal processes, like permeability changes at synapses, facilitation, inhibition, excitation or threshold control recur everywhere in the nervous system.

Almost any visual act involves millions of similar visual receptors, hundreds of millions of similar synaptic processes, etc. This means that the specialized mechanisms of vision are most probably structured from few basic components, combined in endless varieties of neuronal networks. In a sense one can view them as rote mechanisms. Complex systems of these neuronal rote mechanisms cannot be studied sensibly at the detailed 'rote' level and will usually be studied at a more molar level, say at the level of cells and cell networks. There the organismic functions of the complex systems become visible and the networks may prove to be smart systems resonating to ecologically relevant higher-order variables of the environment.

It is not so much the kind of elementary processes that make up a system, but rather their efficient, surprising and purposive combination that determines whether the system can or should be called *smart*. As soon as the

human observer of the process loses track of the role of the goings-on because of the mass of reiterated detail, he is watching rote mechanisms. The distinction rote versus smart-components of a complex purposive system (functional mechanism) is very much in the eye of the beholder.

Smart neuronal systems tuned to complex but informative aspects of the environment can also be called *brain programs* (Young 1978) written in *neurones*, the flexible construction set (metaphorically 'programming language') of the nervous system. Such terminology invites further scrutiny lest it be mistakenly assumed that we have software in our nervous systems or that the nervous system functions as a present-day computer.

Also a computer program might perform some functions having to do with higher-order variables at some sensing system, for example determining coherences or invariants in masses of signals, pixels or numbers. The program is then specially 'tuned' to these higher-order variables. It is only if we go down to the deeper levels of the details of the procedures and functions, or deeper still to the level of the basic instruction set of the cpu (central processing unit) that we find 'rote' mechanisms.

Even though this means that computer programs can be 'smart' in almost the same sense as brain programs, they cannot be directly compared. Brain programs differ fundamentally from digital computer programs in that they are non-relocatable, non-digital, usually non-algorithmic and always 'wetware' rather than software (van de Grind 1984 and 1988). They do not *use* our memory, they *are* our memory, because they reflect the structure of our experiential world (op. cit.). Furthermore, they are self-organizing and not like computer programs products of the activity of an external agent (human programmer).

A *program* is a *plan for action*, and this useful general concept should of course not be pre-empted by the computer community.

#### 4 Having a Body Makes a Great Difference

I would like to suggest that smart mechanisms, which are programs (=plans for action) laid down in the nervous system (in *neurones*) and in the body-form (form-function synergy) are mainly different from present-day computer programs because they have to refer to a body and to the real-time non-digital interaction between body and environment. Computers do not (yet?) have a body in any similar sense and computer programs thus always act on *symbolic* representations of the outer world and of their own interface with the outer world. Computers in fact only have a symbolic interface with educated humans. They do not act on the organic and anorganic environment in the direct service of their own survival and they do not sense their own interior and surface. They have internal representations in the form of symbol

structures, where the coding, the mapping of input into representation and output, is arbitrary, conventional. Their activity is 'mediated' by explicit symbol structures. Moreover, the 'meaning' of the internal symbol structures lies in the external interpretation by the skilled user. A computer is a tool, not an autonomous system or *agent*. Having a body (rather than having some spatial structure unsensed by and unrepresented in and irrelevant to the system itself) makes a great difference.

In the discussion on 'direct' perception (Ullman 1980) one can recognize several confusions which center on the point of symbol manipulation (mediated) versus body manipulation (direct). Symbol structures have to be constructed and require rule-governed processes (Carello et al. 1984). Body control requires tuning to ecologically relevant aspects of the environment and law governed processes (op. cit.). If one studies sensorily-guided bodily actions, as most adherents of the 'direct perception' theory do, it is sensible to attempt to circumvent postulates about internal representations, mediation, etc. The information relevant to the sensorily-guided bodily actions resides in the environment, the body form, the interface between body and environment and the smart mechanisms tuned to the peculiarities of the situation. No independent symbolic (conventional) representation is needed to replace the 'real things', because the latter are always there and ready to go when needed. Physical laws always hold and work. Thus the fish need not construct a neuronal representation of the hydrodynamics of swimming, only the appropriate sensory-motor loops, the smart mechanisms, are needed. The rest of the required 'knowledge' is hidden in the body-form and at the interface between body and water. This is a law-governed continuous system. It is more sensible in this case to use the metaphor 'tuning' to the environment than to speak of 'computations' based on sense-data. The swimming programs are smart special-purpose systems that need no internal model of the body, the environment and the hydrodynamic processes. They are an integral part of the whole system as it has evolved in millions of years and the parts need no 'representation' of the other parts of the system, only the appropriate feedback/feedforward signals. The intelligence is distributed, not stored in neurons.

It seems rather far-fetched to call such natural processes 'mediated' or 'computational' or to call the swimming programs in the brain 'algorithms'. If one chooses to do so, it is hard to see why an old-fashioned balance or a wind-mill should not be called an 'algorithm' or why the bending of a tree in the wind should not be called a computation. In my opinion natural law-governed processes should not be called computational or algorithmic. It is first when we make models of them involving symbol structures, that is when we work with representations rather than the real thing, that the words computation and algorithm can be, or even should be introduced. Then we are in the rule-governed domain.

In 'mediated' theories of perception one or more of the postulated stages involve symbol structures (i.e. internal representations), where the nature of the symbols, of the internal codes, is in principle arbitrary, that is, a matter of convention. In 'direct' theories there may be more stages or not, but the meaning of the internal activity lies in the behavioural action as a whole. There the code is not arbitrary (conventional) but specific to the problem and not to be understood in separation from the functional aspects of the whole situation.

In the discussion on direct visual perception (Ullman 1980) one can also find some confusion regarding the decomposition problem. The fixed-action patterns of biology are special-purpose and cannot be broken down into components by the performing organism itself. This need not prevent us, as external observers, from describing components of these fixed-action patterns which also occur in other behaviour! Similarly, smart mechanisms may contain externally discernable components, but these components can only be used in the preordained way within the smart mechanism. The decomposition choice does not exist within the tuned mechanisms of perception, it only exists for the external observer.

## 5. The Modularity of Vision

It is nowadays clear that the visual system is not a single functional entity. It consists of many specialized ('smart') subsystems working mostly in parallel. Sometimes these 'modules' are independent of each other, sometimes they work in a coordinated fashion. The activities in most of these subsystems are cognitively impenetrable. In a future contribution I will present a brief, but I think compelling, overview of some of the findings from psychophysical studies of vision and from the neurosciences that lead to the following conclusion:

*Visual perception is served by a true multiplicity of both functionally and neuro-anatomically discernable, relatively independent, modules.*

This modularity holds for cognitively impenetrable aspects of vision, like fast sensorimotor control, as well as for perceptual cognition ('knowing by perceiving').

This modularity thesis and the idea that smart mechanisms are the modules of the system for perceptual cognition suggest two major questions of system-decomposition:

1. What is the character, role and internal structure of the smart modules?
2. How do the smart modules cooperate?

ad 1. In terms of theories of direct perception, it is to be expected that the smart modules have direct access to the outer world. The sensorium and

motorium have to be 'transparent' to the smart modules. This assumption clashes with mediated or homunculus-oriented (Attneave 1961) theories, where it is supposed that the processor modules operate on a kind of inner screen representation of the world (the sensorium) or on a pianokeyboard-like representation of potential organismic actions (the motorium). Computational theories tend to start from the same 'serial' processing assumptions as the classical inner-screen theories. It is therefore necessary for supporters of the direct theory of perception to elucidate in what sense the sensorium and motorium are transparent to the smart mechanisms of perception and action. As I have argued more extensively elsewhere (van de Grind 1987), each cognitively impenetrable smart mechanism with a sensorimotor function is probably basically a 'look-up-table-like' remapping of the optic array in a 'smart matrix' or 'feature map' as Barlow (1981, 1986) calls it. These mappings are such that 'computations' are circumvented. The smartness is implemented in the mapping in the same way that the hydrodynamics of swimming is mapped into (stamped on) the body form of a fish. Several concrete examples are presented in van de Grind (1988). Also one of the mappings suggested by Barlow (1986) that can estimate the position of the focus of expansion without doing a single explicit calculation, is a good example of a 'non-computational' smart mechanism.

ad 2. The above multiplicity-thesis forces one to think about the cooperation of smart mechanisms. For example head movements induced by the auditory localization of 'dangerous' sounds have implications for eye movements. Thus there should at least be some coupling between the smart mechanisms of visually guided and of auditorially guided head movements and eye movements. Coupling, coordination, organization imply a loss of degrees of freedom. There are basically two ways of implementing coordinated behaviour of a number of modules.

One possibility is a purely heterarchical organization, where there are causal couplings directly between the modules involved. This is a lateral network type of interaction with communication (causal coupling) between modules which are all at the same level. Working out the possibilities is a matter of synergetics, to the extent that it includes the science of coordinated behaviour.

The other extreme is hierarchical, where supervisory, command and control modules regulate the interdependence between low-level modules. Such a hierarchy would mean that there is some form of mediation after all, since the low-level modules have to inform their managers (who thus receive only mediated information on the events in the outer world). The managers then give directions to the low-level modules, which thus only get 'mediated' (and possibly only implicit) information on the goals of the organism. In cognitive psychology hierarchical models are in favor.

If cognitively open (neuronal) modules are the supervisors of the communication between the cognitively closed smart modules one would both 'direct' and 'mediated' theories to explain the resulting behaviour at the organismic level. An example of such a mixed account of 'agents' can be found in Koenderink (1986).

A direct-apprehension theory on the other hand would probably have to assume that 'agents' consist of a pure heterarchy of smart mechanisms, because any hierarchy implies mediation between the world and modules higher up in the hierarchy.

The arguments presented so far suggest that the visual system - including visually-guided action-systems - contains smart modules taking care of ecologically important (often very fast) perceptually-guided behaviour. These modules look at, and act on the environment in a direct way. To them the sensorium and motorium are functionally transparent. It is also suggested that this may not be the whole story and that direct theories will probably have to make peace with mediated theories somewhere along the line. Computational approaches might be on the wrong track altogether as far as perceptually-guided muscular activity is concerned (van de Grind, 1988), but might be relevant for the modelling of some other functions involving explicit symbol or world model manipulation.

## 6 The Possible Fine Structure of Visual Smart Modules

If perception is a lot like measuring (van de Grind 1988) and ecological physics studies the question what can be measured, neurobiologists could try to answer the question what the measuring instruments are like.

Single photoreceptors can generate a current pulse for every effectively absorbed photon (for a review, see Bouman et al. 1985). Already at this initial stage the single photon events, the shots of energy, are not in themselves relevant, that is 'informative'. The higher-order physical variables at the receptor level are hidden in the simultaneous-successive order of the isomerizations in the outer segments. To block out spurious events due to thermal isomerizations and to optimize the 'tuning' in space and time to the physical light structure, a number of smart (micro-) machines are necessary, which can be viewed as smart components at a more molar level. Some 18 years ago we developed optimal machines to take care of these problems of tuning to physical structure (see references in Bouman et al. 1985). These optimal machines can be implemented with relatively few components, of which the coincidence detector' (C-unit) is the most prominent one. In such a C-unit incoming events have an effect that diminishes (e.g. exponentially) or 'leaks away' with time. Effects of subsequent and simultaneous events sum ('leaky integration') and if a certain threshold is exceeded an output signal is gene-

rated. Such a combination of leaky integration and threshold - both likely neuronal processes - sets a relative coincidence requirement. A C-unit can act as a decision element (asynchronous logic gate) at low event rates or as a scaler at higher event rates (van de Grind et al. 1971). In combination with neuronal delays in axonal or dendritic pathways, excitatory or inhibitory connections, and other well-known aspects of neuronal interactions, C- units can be used to construct integrators, gates, filters, counters, scalars, etc. A quantitative change of parameters such as the leak-time-constant or the threshold can induce a functional (qualitative) change. The coincidence operator appears to be a rote mechanism in Runeson's sense and yet it is a major candidate member of the restricted neuronal construction kit from which neuronal smart mechanisms are constructed.

The smart remappings enabling the visual system to detect the focus of expansion (Barlow 1986), to estimate ego-velocity or the distance and time-to-nearest-approach of objects (van de Grind et al. 1987) all require the possibility to detect a coincidence of many or few events close together or widely

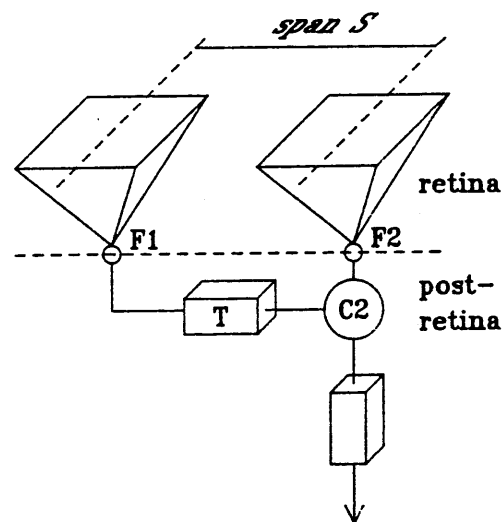


Fig. 1. A 'bilocal' motion detector, which is tuned to the velocity  $S/T$ , where  $S$  is the span and  $T$  the delay of the detector. The symbol  $C2$  represents a 2-fold coincidence (or C-) unit. The receptive fields  $F_1$  and  $F_2$  are the windows on the world of a motion analyzing cortical area, but they also feed into other smart mechanisms in parallel. The velocity-code is of the labeled-line type. Delay  $T$  is actually the difference between the response latency of the pathway from  $F_1$  to  $C2$  and the one from  $F_2$  to  $C2$ .

dispersed in the visual field. Remapping in combination with coincidence detection can make visual processes *direct* almost in the sense of look-up-table operations (op. cit.).

Let us give a specific and well-known example of the power of C-units combined with delays, viz. the velocity-tuned bilocal movement detector. This class of mechanisms has been described in several forms as a neuronal component of the visual systems of rabbits, cats, flies, etc. There is also good evidence that it plays a similar key role in human motion detection (van Doorn et al. 1984, 1985; van de Grind et al. 1983, 1986; Koenderink et al. 1985). Figure 1 summarizes the main idea. A neuronal multiplication-like operation (a two-fold coincidence operator) ensures that the bilocal detector reacts if and only if the signal from field  $F_1$  coincides/correlates with the signal generated  $T$  seconds later in field  $F_2$ .

The bilocal detector is tuned to a velocity  $V = S/T$ , where  $S$  is the span,  $T$  the (differential) delay of the system. It is assumed that the retinal receptive fields  $F_i$  map onto a cortical area specialized in analyzing coherent motion. Since the same retinal fields also map in parallel onto many other cortical areas and subcortical regions they are an integral part ('windows' to the world) of many modules, making the retina 'transparent' to those modules. The considered cortical module for the analysis of motion is supposed to

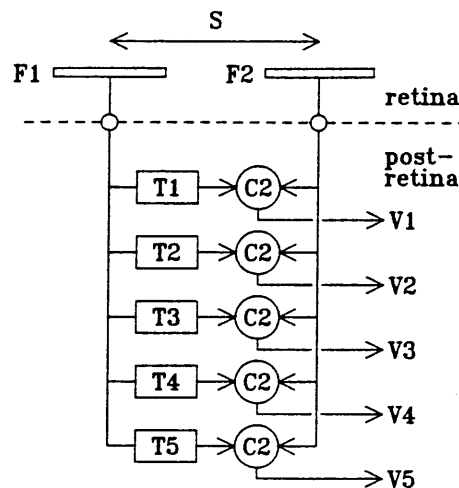


Fig. 2. A hypothetical iso-span column of a motion analyzing cortical area. The outputs of the two-fold coincidence detectors are tuned (as in Figure 1) to the velocities  $V_i = S/T_i$  and if  $T_i < T_{i+1}$  for all  $i$ , then  $V_i > V_{i+1}$ .

consist of equal span columns (Figure 2) or equal delay columns or both. The remapping is such that a labeled-line code for velocity classes is set up. (Due to the finite tuning bandwidth the velocity code across the ensemble of fibers is continuous rather than discrete. It is 'interpolatable').

The feature map in a system with columns like the one illustrated in Figure 2 can be used in many kinds of subsequent functional remappings. To each stage the previous ones are functionally transparent even though these previous stages might act through other output mappings in the service of other kinds of behaviour.

Obviously accelerations or decelerations could be determined by a remapping of the column outputs of the motion analysis system. All one has to postulate is a similar bilocal operation on velocity line  $V_i$  of one column and of  $V_{i+j}$  of a neighbouring column. However, there is no evidence whatsoever for a remapping into the acceleration domain. More probable remappings are discussed elsewhere (van de Grind 1988). The bilocal velocity detector could be a smart component of a general optic flow analysis module as well (vide infra).

It may be sufficiently clear from these brief remarks that remappings together with delay- and coincidence operations enable the nervous system to circumvent the necessity to do explicit numerical calculations on visual data. The proposed visual modularity is non-computational. Nevertheless one can maintain that implicitly velocity is 'computed' in a bilocal movement detector as displacement per unit time (a difference operator rather than differentiation). This is to a certain extent a matter of taste in choosing one's terminology. Yet the sketched system is in many respects a smart mechanism in Runeson's sense. It is special-purpose and 'tuned' to informative aspects of the optic array. The 'calculations' are not done in the symbol-domain as in a digital computer algorithm, but in the signal-domain, more like the processes in an analog computer. The remappings, requiring millions of axons, are rote-like operations. Yet they clearly capitalize on the specific possibilities of the nervous system and abstract higher-order, global, aspects of the optic array. In man-made machines wires are troublesome, but 32 bit cpu's are easy to install, in the nervous system the opposite is more nearly true. It is the curious ease with which regions of the nervous system establish an ordered mapping onto other regions, with the ordering determined by functional correlations (feature maps), that determines the functional architecture of the visual system (van de Grind 1988).

## 7 Neuronal Analysis of Some Aspects of the Optic Flow

Changes in angular relations of visual landmark directions at different points of the optic array can provide information about the spatial lay-out of the environment and about self-motion (e.g. Koenderink 1985, 1986). It has been

shown (op. cit.) that the visual flow field can be completely characterized in principle by the expansion, vorticity and shear components. Expansion detection or 'looming' is also involved in measuring time-to-contact (e.g. Le and Young 1985). Figure 3 symbolizes the basic principle of (local) expansion detection. The circles A-D symbolize elementary movement detectors, e.g. of the bilocal type discussed above. The coincidence operator C4 (Figure 3 requires the more or less simultaneous activity of all four contributing movement detectors in order to respond.

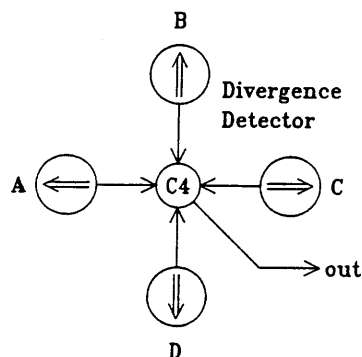


Fig. 3. A divergence, expansion or looming detector consisting of four bilocal motion detectors A-D (circles), with the indicated preference direction (arrows in the circles), and a four-fold C-unit. This 'looming' detector is tuned to the single expansion velocity that corresponds to the velocity tuning of the four identical bilocal motion detectors.

The suggestion of Figure 3 is based on results in ecological optics. Only vision research can tell us whether the organism can indeed pick up the higher-order variables suggested by ecological optics. Thus the first question is 'do we have looming detectors?' If the answer from psychophysical studies is 'yes', a next question arises: What are the detailed properties of these detectors and how could they be implemented (in principle) in neuronal networks? Answers to this question are neurobiological hypotheses that can be tested. This is the neuroreductionistic approach (van de Grind 1984) so disliked by 'pure' psychophysicists or phenomenologists. As far as I can see it is the only bridge between the behavioural and neurobiological domains, and as such indispensable to those adhering to a physicalist metatheory on the mind-brain problem (see also Dalenoort 1987). In the following the pathway from ecological optics to the neurobiology of smart mechanisms will be sketched in rough outline with the help of a specific example. This example

the looming detector, is not meant to be important in itself, at least not in the present context. Here I mainly want to draw attention to the reasoning-Gestalt in neuroreductionism.

H. Korteling, B. de Graaf, and I have designed some psychophysical experiments aiming at a further decomposition of the expansion detector proposed in Figure 3. After replicating the experiments of Regan and Beverley (1978) and corroborating their results, we extended them in several ways. With looming circles, line pairs and dot groups we analyzed the possible combination of movement detectors in one and two dimensional image expansions. Experimental details and a precise description of the results will be given elsewhere. Here I single out some salient results shedding light on our present discussion:

- Adaptation to horizontally directed expansion in a frontoparallel plane elevated the threshold for horizontal but not for vertical expansion detection. A two-dimensional expansion used as test stimulus after the strictly horizontal adaptation looked like a vertical expansion. (E.g. expanding circles then look like expanding ellipses with a vertical long axis, etc). This must mean that the pair A-C and the pair B-D in Figure 3 can adapt independently.

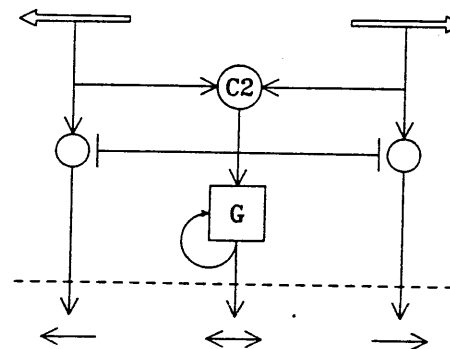


Fig. 4. A one-dimensional expansion detector. If there is no simultaneous output of the two motion detectors converging at the C2-unit, no expansion is seen, the threshold for expansion detection does not rise, and the motion detectors function independently. If there is expansion (at the tuning velocity) C2 is activated and the two contributing motion detector outputs are both suppressed. (Inhibition is symbolized by the T-endings of lines). The gain box G slowly decreases the sensitivity during sustained expansion stimulation and thus increases the threshold for expansion detection after adaptation. Obviously the relay cells in the individual motion channels might also act as gain controls, but that is not relevant to the present discussion.

- Ordinary one-dimensional motion aftereffects (similar to the well-known waterfall aftereffect) do not seem to occur for the individual movement components if the *relations* between these components make the combined pattern into a different meaningful movement Gestalt. If this Gestalt is an expansion the aftereffect looks like a movement in depth, not like two oppositely directed movements in a plane. Thus we were led to a detector model consisting of separate one dimensional looming-direction selective components. The component structure is sketched in Figure 4.

The fact that unidirectional expansion overrides the detection of local component movements is incorporated in this model by the inhibition of single motion-detector channels by the output of the coincidence unit C2.

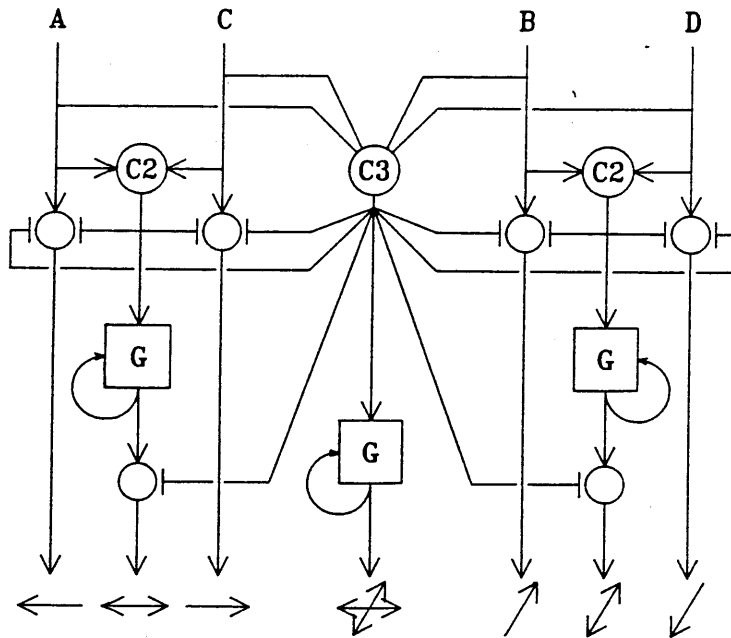


Fig. 5. A two-dimensional expansion detector. Bilocal motion detectors A-D are arranged in the retinal plane as indicated in Figure 3 but only their output lines are shown here to simplify the drawing. C-unit C3 reacts if at least 3 of the four motion detectors are active (almost) simultaneously. In that case the one-dimensional expansion channels and the individual motion detector outputs are suppressed by the higher-order detector.

- A further finding of our research was that even though 1D-expansion did not adapt 2D-expansion (see above) the reverse clearly happens. Again the higher-order (in this case 2D-) relations appear to take precedence. This leads to the next scheme of Figure 5.

- Additional complications have to be faced, since it was found that in expansion adaptation the expansion frequency is much more important than the expansion amplitude. For a fixed frequency, e.g. the optimal one to evoke adaptation effects, the local velocities must of course be proportional to the amplitude of the periodic expansion. Thus, since the amplitude proved to be not critical, the input to our expansion detectors cannot simply be a set of motion detectors all tuned to one velocity. On the contrary a wide range of velocity-tunings must feed into the detector system at the point A-D, if basic velocity-tuned motion detectors are involved at all. In fact it is easy to think of a 'smarter' solution, as sketched in Figure 6.

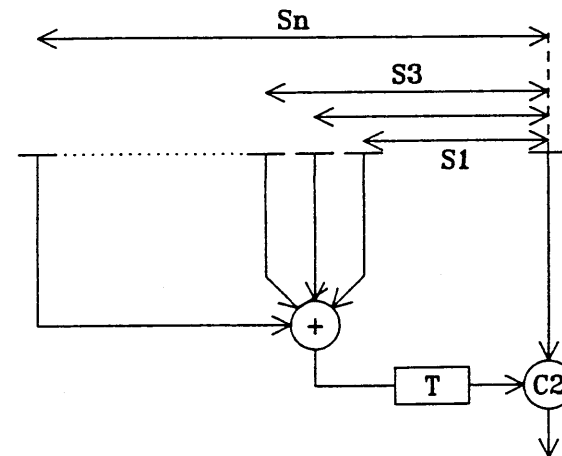


Fig. 6. A wide-velocity-band motion detector. Only the expansion frequency of a periodically expanding stimulus is relevant to the adaptation, not the expansion velocity. Therefore the individual component motion detectors in an expansion detector should not be as sharply tuned in the velocity domain as the bilocal detectors are. A unit as sketched in this figure combines many spans with a single delay and is thus tuned to a wide range of velocities. It can replace the bilocal motion detectors in the previous models of the expansion detector.



In Figure 6 the C-unit C2 is tuned to a whole range of velocities (from  $S_1/T$  to  $S_n/T$ ) and has a range of spans (from  $S_1$  to  $S_n$ ). It is a velocity wide-band unit. Such units have been found electrophysiologically (Orban et al. 1981) so it is nice that we have just invented a function for them. Only combined neuro-biological and psychophysical experiments specifically aimed at testing these proposals and at developing them further will eventually lead to a precise smart-mechanism model of expansion information pick-up. The above line of reasoning illustrates how neuroreductionism works and how empirically untenable assumptions are replaced one by one in the process of model evolution. Only discrepancies between predictions and findings fuel this process.

In conclusion, the example shows that a detailed analysis of potential smart mechanisms (which are suggested by ecological physics) can lead to implementation proposals, which are neuro-biologically testable hypotheses on brain programs. In this sense the concept of the smart mechanism can fulfill a bridge function between psychology and the neurosciences. It thus gives a body to a soul.

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